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Quiet Supersonic Jet Engine Performance Tradeoff Analysis Using a Response Surface Methodology Approach

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ABSTRACT

Recent market studies indicate a renewed interest for a quiet Supersonic Business Jet (SBJ). The success of such a program will be strongly dependent upon the achievement of stringent engine noise, emissions and fuel consumption goals. This paper demonstrates the use of advanced design methods to develop a parametric design space exploration environment which will be ultimately used for the identification of an engine concept capable of satisfying acoustic levels imposed by FAR part 36 (stage IV) and NO_x and CO_2 standards as stated in the 1996 ICAO. The engine performance is modeled through the use of Response Surface and Design of Experiments Techniques, enabling the designer/decision-maker to change initial engine parameter values to detect the effects of the responses in a time efficient manner. Engine performance and engine weight results are obtained through physics-based engine analysis codes developed by NASA. An SBJ airframe baseline model is used in conjunction with the engine performance data and executed through a synthesis and sizing code to simulate a supersonic mission. This paper focuses on the tradeoffs associated with noise, emissions and specific fuel consumption of the supersonic engine by employing design parameters such as overall pressure ratio, fan pressure ratio, turbine inlet temperature and throttle ratio. Finally, an optimal engine combination is created to satisfy all the constraints imposed by the aforementioned regulations for a particular mission configuration. Using a statistical analysis package, the designer has the ability to analyze tradeoffs that allows adjustments to be made to certain parameters that, although may compromise others, will still allow the system to fall within engine regulatory limits.

NOMENCLATURE

SBJ	Supersonic Business Jet
RSM	Response Surface Methodology
THR	Throttle Ratio
FPR	Fan Pressure Ratio
OPR	Overall Pressure Ratio
T4	Turbine Inlet Temperature, (deg. F)
CEF	High Pressure Compressor Efficiency
HTEF	High Pressure Turbine Efficiency
T/W	Thrust to Weight Ratio of the Aircraft
TSFC	Thrust Specific Fuel Consumption
TOFL	Takeoff Field Length, (feet)
LDGFL	Landing Field Length, (feet)
TOGW	Takeoff Gross Weight, (lbs)
VAPP	Approach Velocity, (knots)

INTRODUCTION

The globalization of business and the emergence of new markets around the world have prompted aerospace companies to focus more on fast and efficient business transportation. Over the past decade, economic markets in distant regions of the world such as South-East Asia, Japan, and Europe have become integral players in global trade, making them a frequent destination for business travelers. This demand has triggered an increase in subsonic business jet production in the past decade.

The Concorde SST has proven to be an economical disappointment and with its life-cycle nearing an end, a supersonic business transport replacement is currently in the works. The SBJ concept has shown promise in preliminary design studies that with the infusion of certain technologies, an economically viable vehicle can be attained in the corporate market. This vehicle will be particularly appealing to higher level executives that can afford to pay a premium for fast transportation. Furthermore, it will also serve as a springboard from which to launch into the commercial supersonic market with less risk involved. The initial development costs of a 300 pax supersonic transport can thus be amortized over multiple SBJ sales. There is also a potential for military derivatives. The SBJ design may be altered to serve as a rescue aircraft, a cargo variant or as a strategic operator for defense. Existing turbofan engines in fighter jets are roughly in the same thrust class and can aid in the design for a propulsion system.

The success of the supersonic business jet depends largely on its ability to be technically feasible and economically viable. The design for performance paradigm in aerospace design has been replaced by an emphasis on affordability which implies the SBJ will have to be price-competitive with its subsonic counterparts. It must also be capable of satisfying regulations and be certifiable. Sonic boom for supersonic aircraft is a major concern, and there is continuing research in this area, which entails solving complex aerodynamic issues. This research and the prospects for a "low boom" airframe design for the supersonic business jet are discussed in reference 1. With an increasing emphasis on environmental effects, the focus for the design of this aircraft must address these effects as well as the need for good economic performance. The airframe must be designed for low sonic boom, as discussed above, and the engine must meet or improve on noise and emissions requirements. The Federal Aviation Administration (FAA) continues to impose stringent margins for landing and takeoff noise and NO_x and CO_2 emissions that will become a difficult challenge for future aircraft to fulfill. Entities like Boeing, Northrop Grumman, NASA, DARPA[1] and Gulfstream have dedicated research to aid in the development of an environmentally friendly supersonic vehicle.

The objective for this study is to demonstrate the methods and technologies that can facilitate or assist industry in the design of a quiet SBJ. The propulsion study presented in this paper is part of a larger investigation into the complete aircraft. See reference 1 for a discussion of the aircraft aerodynamics and the airframe design for low sonic boom and reference 2 for a discussion on advanced technologies that may be applied to the SBJ concept. The comprehensive design study [Ref. 1] encompasses the propulsion design space that is explored in this paper. It also integrates an economic and sonic boom analysis which enables the designer to identify impacts on operating costs and sonic boom overpressures for example, by varying engine cycle parameters.

[1] Defense Advanced Research Projects Agency

The focus of this study is dedicated to three main areas of concern in supersonic engine design: noise, emissions and fuel consumption.

BASELINE DESIGN CONFIGURATION

The methods that are described in the following sub-sections describe the methodology applied to the propulsion design space exploration. Although the methodology used in the aerodynamics study is fundamentally the same, the design variables and requirements are different and therefore the analysis varies. The finalized version of the aircraft is created through optimization techniques that are described further in this paper. Figure 1 illustrates the geometry of the baseline version of the aircraft. The reader is referred to reference 3 for further details of this version.

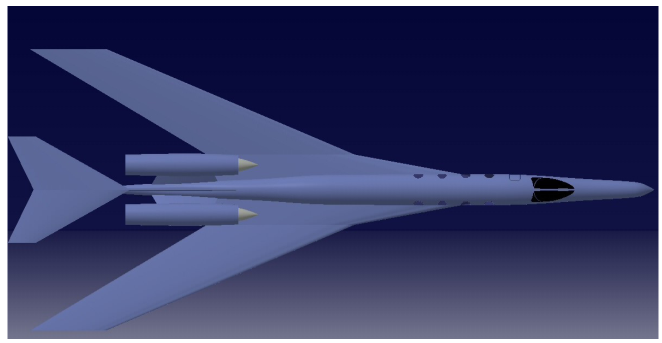

Figure 1: SBJ Baseline Design.

The mission requirements for this vehicle are obtained from a representative notional design mission and the National Business Aircraft Association (NBAA). [Ref. 4] Although Mach number, altitude and range variation trades were performed, this paper concentrates on the propulsion system designed for an aircraft cruise Mach number of 1.8 at a beginning of cruise altitude of 56,700 feet followed by cruise climb to a final altitude of 60,000 feet at the end of the cruise. The total range from the beginning of climb to the bottom of descent is 4,000 nautical miles. In addition, the mission allows for sufficient fuel for NBAA IFR reserves equal to a 30 minute holding pattern at 10,000 ft. Figure 2 depicts this SBJ mission profile.

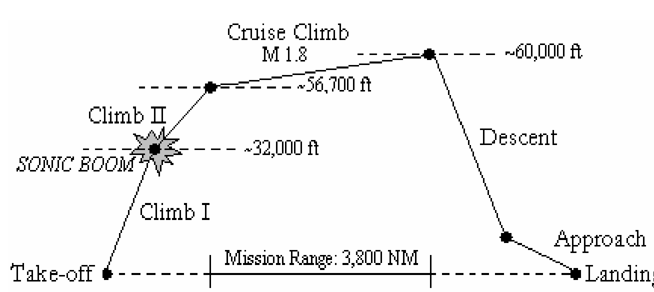

Figure 2: SBJ Mission Profile.

MODELING AND SIMULATION ENVIRONMENT

The methodology applied to study the design environment of the engine uses the Technology Identification, Evaluation and Selection (TIES) process, which has been pioneered and used successfully at the Aerospace Systems Design Laboratory. This process is described in detail in reference 5.

The TIES method contains nine steps for implementation. The first step defines the problem. This involves translating the qualitative needs and requirements of the customer into system product and process parameters. Brainstorming techniques and Quality Function Deployment (QFD) facilitate this process. Following this step, baseline and alternative concepts are identified via a morphological matrix. A baseline engine is selected from this matrix that contains an engine concept with state of the art technologies in terms of engine cycle and weight parameters. A complete design space for the aircraft design and mission is then created through a modeling and simulation environment by means of a physics-based set of analysis codes. These codes, which will be described later, are very time consuming to run in order to investigate all the engine design options of interest. Instead, a procedure called design of experiments (DoE) is employed. To run a DoE, sets of input variables and output responses are defined. In the fourth step, the DoE is executed in a prescribed way to develop a set of data large enough so that the responses can be related to the input parameters by means of a meta-model.

The Response Surface Methodology is a multivariate regression technique developed to model the responses of a complex system using a set of polynomial equations. RSM is based on the design of experiments technique, which ensures variable independence (orthogonality) and yields the best achievable accuracy for a given amount of experimental effort. The responses are typically modeled using a second order quadratic equation of the form below:

$$R = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i=1}^{k} b_{ii} x_i^2 + \sum_{i=1}^{k-1} \sum_{j=i+1}^{k} b_{ij} x_i x_j \qquad (1)$$

where b_o is the intercept, b_i is the regression coefficient for the linear (first-degree) terms, b_{ii} is the coefficient for the pure quadratic (second-degree) terms, and b_{ij} is the coefficient for the interaction (cross-product) terms. The terms x_i and x_j are representative of the design chosen variables. The development of these Response Surface Equations is usually referred to as "meta-modeling" of the design space.

In this analysis, a Central Composite Design (CCD) DoE is employed with 145 total cases. Each case executes the physics-base codes in a specified sequence presented in Figure 3. These analysis codes are combined into a script in TCL language to facilitate the implementation of the DoE values for each case into each code. The entire process, from the DoE input until response information output takes 3 minutes to complete for each case using a standard Pentium III processor computer.

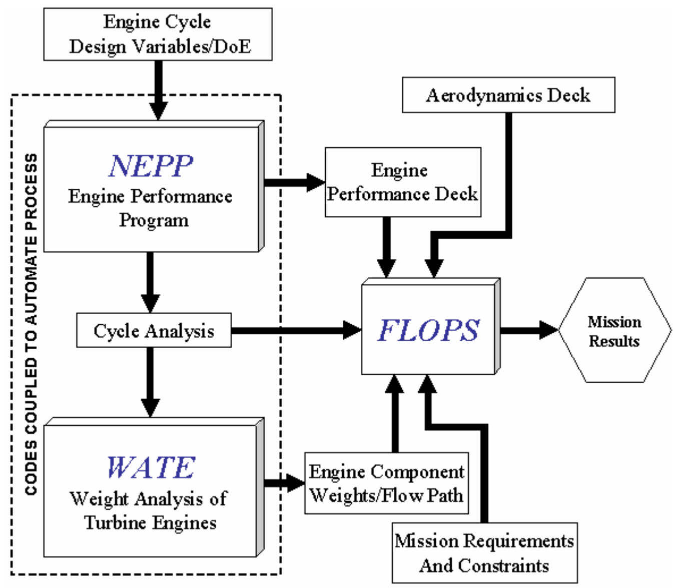

Figure 3: Physics-Based Codes- Execution Process.

There are two main codes used for the analysis portion of the engine, NEPP and WATE. NEPP (NASA Engine Performance Program) [Ref. 6] is a NASA and propulsion industry developed program that analyzes the one-dimensional, aero- and thermodynamic characteristic of the flow going through the engine. NEPP simulates an engine by defining basic engine components and allowing the user to "link" them together to form a complete engine. The user can further define each engine component as well as its operational points, and NEPP will integrate all of the components to form an engine cycle. Based on these inputs, NEPP will estimate/predict the performance of the engine in the form of an engine deck as well as the flow properties (i.e. mass flow, pressure, and temperature) at each engine station.

In addition to the thermodynamic analysis, an estimation of the weight and physical properties of the engine must be determined. The program used for this purpose is WATE (Weight Analysis of Turbine Engines) [Ref 7.] WATE is also a NASA developed program which predicts the flow path as well as the weight and envelope dimensions of large and small gas turbine engines. WATE is able to predict these results based on the cycle analysis output from NEPP as well as a combination of correlation and preliminary design procedures that are sensitive to blade geometry, operating conditions, material properties, shaft speed, hub-tip ratio, etc. The weight estimate provided by WATE is a conservative one since it does an iterative search through the entire user-defined flight envelope to determine the most critical condition for each engine component.

In order to obtain useful mission data, a mission sizing and synthesis code must be employed that can generate responses such as Take-off gross weight (TOGW), landing and takeoff field lengths, etc. To compute these parameters the flight optimization code (FLOPS) [Ref. 7] is used. FLOPS is a multidisciplinary system of computer programs for the conceptual and preliminary design and evaluation of advanced aircraft concepts. It consists of nine primary modules; weights, aerodynamics, internal engine cycle analysis (not used for this study), propulsion data scaling and interpolation, mission performance, takeoff and landing, noise footprint, internal cost analysis (not used for this study), and program control. The noise analysis carried out in this investigation which includes FAR sideline and flyover noise calculations, is determined by a modified version of FOOTPR integrated into FLOPS under the name NOISIN.

Table 1 below contains a list of the cycle parameters that are chosen as input parameters for the DoE. Minimum, nominal and maximum values are given for each parameter. Engine cycle parameters not included in this list are the fan efficiency and the low pressure turbine efficiency. These parameters were held fixed at 0.89/0.9 for the fan and low pressure turbine, respectively.

Design Variable	Min	Nominal	Max
Throttle Ratio (THR)	1.2	1.215	1.23
Fan Pressure Ratio (FPR)	1.7	2.35	3
Overall Pressure Ratio (OPR)	25	27	29
Turbine Inlet Temperature (T4) deg. F	3300	3350	3400
High Pressure Compressor Efficiency (CEF)	0.89	0.9	0.91
High Pressure Turbine Efficiency (HTEF)	0.89	0.905	0.92
Thrust to Weight of the Aircraft	0.4	0.425	0.45
Wing Area (ft^2)	2500	2800	3100

Table 1: Design Variables and Ranges for DoE.

The design variables are chosen as a result of their respective influence in an engine cycle. In this study it is also useful to have a throttle ratio capability which allows the designer to design for the most demanding portion of the mission. The purpose is to increase thrust at a specific flight condition. Throttle ratio is used for sizing engines that will fly at high inlet temperature conditions. Generally, a turbine engine will have to reduce the turbine inlet temperature, T4, in order not to over-speed the engine at a high Mach number (high temperature) cruise condition and top-of-climb. This is an unacceptable penalty for an engine that must cruise for long periods of time. However, it is possible to redesign the high pressure turbine so that it can operate at maximum T4 at top-of-climb, but this is done at the expense of a reduced T4 at lower inlet temperatures. In particular, takeoff T4 and thus takeoff thrust will be reduced. In simplest terms, the throttle ratio is the ratio of maximum T4 at top-of-climb to maximum T4 at sea level static, standard day conditions. The transition through sonic speed at 32,000 ft is also considered and captured in the choice of a throttle ratio range. The enormous drag rise at this condition requires significant thrust from the engine. Without the possibility of afterburners, the engine must be designed to produce sufficient thrust. The fan pressure ratio range is large enough to model an engine design with a single and dual stage fan. The overall pressure ratio range in conjunction with the FPR is used to determine the high-pressure compressor pressure ratio that is required as an input into NEPP. There is little variation specified for the turbine inlet temperature due its sensitivity in the analysis codes that will cause many cases to fail. The component efficiency ranges allow the designer to represent improvements in component design and see how it can change the design of an engine. The two final variables are used in FLOPS as tools to tailor the amalgamation of the aircraft to the engine. The baseline (nominal values) is initially run through the codes and bounds are set, verifying that the codes can handle all the possible combinations. A mixed-flow turbofan architecture is selected as modified in the SBJ baseline. Aircraft baseline and engine performance results are shown in Table 2. A flow-path illustration of the engine is shown in Figure 4.

Aircraft and Engine Baseline Results		
Total Engine Pod Weight	8607	lbs
TOGW	159730	lbs
Sea-level Static Thrust	35000	lbs/engine
Bypass Ratio	0.67	-
CO_2	48.1	(lbs/NM)
NO_x (% reduction from 2004)	40	%
Flyover Noise	82	dBA
Sideline Noise	89	dBA
TSFC (cruise)	1.24	-
TOFL	6562	ft
LDGFL	6688	ft
VAPP	128	knots
Aircraft Empty Weight	70861	lbs
BlockFuel	88869	lbs

Table 2: Baseline Case Results

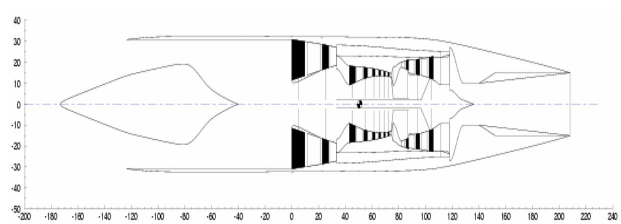

Figure 4: Engine Flow-Path Results.

FIGURES OF MERIT

One of the main purposes of this study is to provide an understanding of the driving parameters that contribute to engine noise, emissions and high fuel consumption. This section defines the requirements for these three responses.

NOISE REGULATIONS

Noise considerations are not new to aircraft and engine design. In the United States, Federal standards adopted the Federal Aviation Regulations (FAR) Part 36 standard in 1969. Since then, the FAA has amended this regulation 15 times covering all other categories and types of aircraft. The International Civil Aviation Organization (ICAO) has likewise established a set of aircraft noise requirements designated Annex 16. In June 2001, ICAO adopted a new Chapter 4 noise standard, more stringent than that contained in Chapter 3. Commencing January 1st 2006, the new standard will apply to newly certificated airplanes. The current forecast for SBJ production suggests production in 10 years. Consequently, it must meet stage 4 noise requirements implemented in 2006. This study has considered such restrictions and has instituted an appropriate constraint throughout the analysis.

The ICAO and FAA have introduced two ways of monitoring aircraft takeoff noise. Many large airports have measuring systems in fixed locations that are activated when an aircraft overhead exceeds the A-weighted sound level beyond that of a given threshold level. These stations measure three types of noise: sideline, flyover and approach. The sideline noise is the maximum noise observed along a parallel line of reference to the runway. It is located approximately perpendicular to lift-off where a noise peak is heard. Flyover noise is measured from an observer located vertically beneath the aircraft a distance from brake-release on the runway. Finally, approach noise is likewise measured beneath the aircraft at a given distance from touch-down. All these metrics are illustrated in Figure 5.

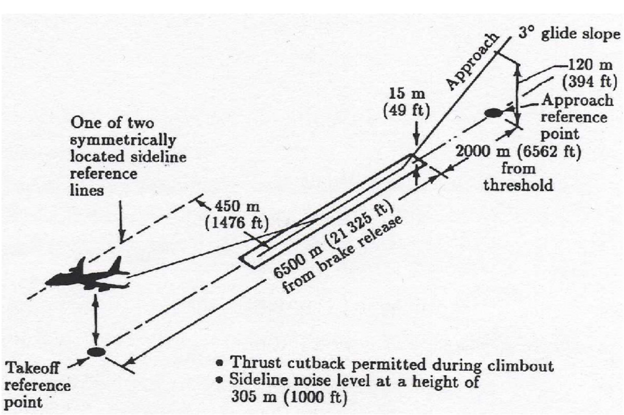

Figure 5: Noise Measurement Locations [Ref. 9].

Aircraft noise is generated primarily by two sources. During takeoff, the dominant noise sources are from the fan and the exhaust. The high-speed rotation of the fan blades causes their tips to reach supersonic speeds creating a loud fan-blade noise when they break through the air. Jet noise is the turbulent mixing of the exhaust air from the nozzle with the surrounding atmosphere. In supersonic engines, there are shock structure related noise components that are additionally sound intensive. Engine noise suppression techniques will be discussed in the results portion of this paper.

Regulatory noise limits are dependent upon the aircraft's size and weight. Figure 6 and Figure 7 show what the flyover and sideline noise limits are for ICAO chapter 3 certification. With the production of the SBJ occurring past the 2006 chapter 4 implementation, this study must incorporate the extra margin necessary for chapter 4 certification. The regulation for all new aircraft will be a 10dBA cumulative reduction (below chapter 3) across the three measurement points. There must be a minimum of 2 dBA improvement on each individual location.

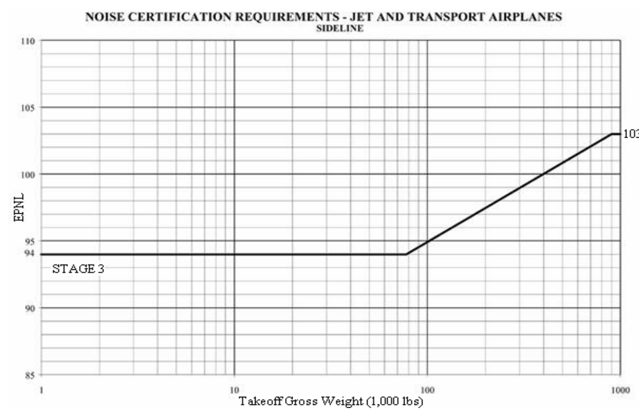

Figure 6: ICAO Chap. 3 Sideline Noise Regulations [Ref. 10]

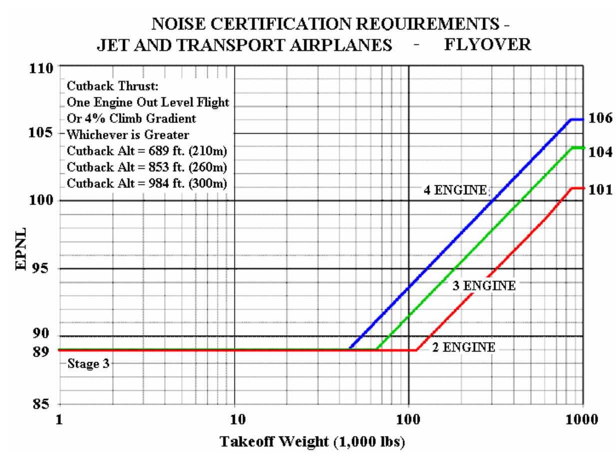

Figure 7: ICAO Chap. 3 Flyover Noise Regulations [Ref. 10].

EMISSIONS REGULATIONS

The effects of aircraft engine emissions on the environment are perhaps the most harmful in the upper atmosphere. These changes in atmospheric composition have severe climatic impacts on the planet. The two most abundant products of jet fuel combustion are carbon dioxide (CO_2) and water vapor (H_2O). For supersonic vehicles that cruise at very high altitudes the effects of CO_2 can be considerable. Although CO_2 does not contribute directly to ozone depletion, it still affects stratospheric cooling resulting in changes in atmospheric thermal stratification and eventually reduced ozone concentrations. The next most significant pollutant is nitrogen oxide (NO_x) emissions. Like CO_2, it plays a dominant role at high altitudes. Unlike its counterpart however, it does directly affect the ozone photochemistry of the upper troposphere (UT) and lower stratosphere (LS). Ozone in the UT and LS is expected to increase as a result of NO_x increases. At higher altitudes, increases in NO_x lead to decreases in the stratospheric ozone layer.

The ICAO Committee on Aviation Environmental Protection (CAEP) is in the process of evaluating stricter standards for engine emissions during the landing and takeoff phases. This study focuses on emissions production during this Landing and Takeoff cycle (LTO). In these phases, atmospheric mixing occurs with pollutants emitted from aircraft flying below 3000 ft. The LTO cycle begins when the airplane enters the mixing zone during the approach and descent phases from cruising altitudes. It continues in effect throughout the landing and taxiing stages. Similarly, the cycle includes the takeoff portions of flight. All these segments are illustrated in Figure 8.

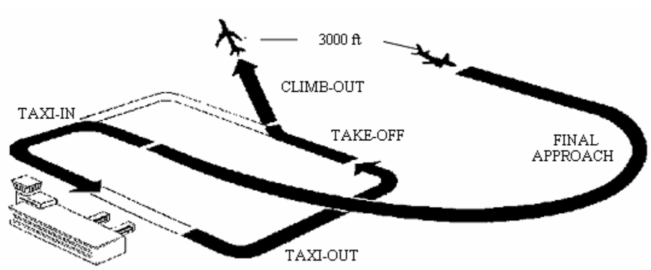

Figure 8: ICAO LTO Cycle for Emission Certification.

Current state-of-the-art subsonic engine technology meets the 1996 ICAO NO_x emission standards. However, the U.S. EPA and European counterparts are applying pressure for additional NO_x reductions in the LTO cycle. Furthermore, these agencies are developing standards for NOx emissions not yet established for cruise conditions. Furthermore, there are no current standards that apply specifically to supersonic commercial aircraft. This SBJ analysis calculates a given percentage NOx reduction in the LTO cycle from 2004 ICAO levels shown in Figure 9.

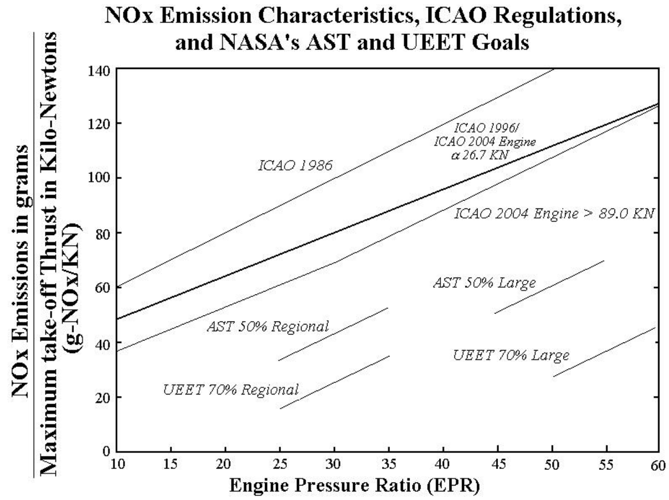

Figure 9: ICAO Regulation Standards [Ref 11].

FUEL CONSUMPTION

In the airline industry, operating costs determine survival. These costs account for all direct and indirect costs incurred by airlines every day. One of the most dominating factors affecting these costs is the cost of fuel. The complexities of fuel price fluctuations are partly due to political issues involving OPEC[2] countries and but primarily driven by the level of consumption of petroleum around the world. Although aircraft fuel consumption is a small percentage of overall fuel usage in the world, the number of aircraft operating will increase substantially in the next few decades increasing the demand for fuel. However, with improvements in engine technologies and pressure from airlines, engine manufacturers have reduced fuel consumption as a primary goal along with reduced noise and emissions. Although specific fuel consumption is the metric of interest, block-fuel, the amount of fuel consumed over the design range is also monitored. An economically viable aircraft relies heavily on the efficiency of its engine. In addition to the aerodynamic design of engine components, the use of advanced material technologies plays a major role in efficient engines [Ref 2]. This study however, shifts the focus to the effects on fuel consumption due to varying cycle parameters.

A list of target values is presented in Table 3. These are determined primarily from certification requirements in conjunction with design goals from specific aerospace entities involved in the SBJ design.

[2] Organization of the Petroleum Exporting Countries

Responses	Target Value
CO_2	50 (lbs/NM)
NO_x	50 % red. from 2004 ICAO
Flyover	88 dBA
Sideline	90 dBA
TSFC (cruise)	1.15 -
Takeoff Gross Weight (TOGW)	150000 lbs
Takeoff Field Length (TOFL)	6500 ft
Landing Field Length (LDGFL)	6500 ft
Approach Velocity (VAPP)	140 knots

Table 3: Target Values for System-Level Responses.

The target value set for CO_2 is also setting a target for mission fuel consumption because there is a direct relationship between the two. Approximately 3 pounds of CO_2 are produced for every pound of fuel burned.

ANALYSIS OF RESULTS

Using the methodology described in the modeling and simulation section, the design space is explored for technical feasibility. The RSM starts with the creation of the orthogonal DoE table using a commercially available statistical package called JMP® [Ref. 12]. A DoE is a table of prescribed settings of the factors or design variables for each propulsion system simulation run. These variable ranges are shown in Table 1. The codes are executed as described in Figure 3. The results or data are then exported back to JMP® to perform a multivariate regression in order to determine the regression coefficients in Equation 1, which completes the creation of the RSEs for each metric listed in Table 3.

These RSEs will be used to perform the actual design space investigation by quickly mapping the design variable settings to the system level responses. The RSEs in the JMP® software allow the designer to manually alter the variable settings without rerunning the time consuming codes. Moreover, the user can graphically determine which response is most sensitive to which design variable(s).

As stated, one of the valuable results of the JMP® analysis is the creation of an environment in which the decision maker can play "what-if" games. This type of environment allows propulsion designers to quickly ascertain the system level impacts of changing propulsion parameters. JMP® allows this to happen by producing prediction profiles, a graphical representation of the partial derivative of each system level response to each design parameter. The prediction profiles of the selected metrics are shown in Figure 10. These profiles graphically show the relative impact of the engine cycle variables on system level responses. The slope of the profiler shows how sensitive each response is to the cycle variables. These plots can also serve as "debuggers" to verify the trends of the responses as function of the design variables. Not only can the general trends be seen, but the actual value of the impacts can be determined. For example, what would happen to flyover noise if one could increase the engine fan pressure ratio from 1.7 to 3? This question can be answered in *real time* by dragging the middle hairline of the FPR profiler to the setting of 3. Such interactive action instructs JMP® to evaluate the RSE that is behind the profiler and the response value of all the metrics is updated. Another useful tool is the ability to compare the impacts of the different design variables against each other. For example, Figure 10 shows that increasing the fan pressure ratio (FPR) significantly decreases CO_2, while increasing the overall pressure ratio (OPR) has a much less significant impact on that metric.

The most important observation from these profiles is that all of these responses are affected significantly by changes in fan pressure ratio. The trends are consistent with experimental data gathered in these fields. Both flyover and sideline noise increase with an increase in fan pressure ratio. As mentioned earlier, flyover noise is measured at a certain distance from the runway vertically beneath the aircraft during takeoff. The primary factors contributing to this are jet and fan noise. Jet noise is produced by the high speed exit velocities of the exhaust air. By increasing the fan pressure ratio, the diameter of the fan decreases and less mass flow is bypassed from the core. As a result, to maintain the same amount of thrust, the mass flow through the core must be exhausted at higher velocities. The same phenomenon occurs with sideline noise. The thrust to weight ratio of the aircraft determines the performance of the aircraft during cruise and climb-out. A high ratio results in bigger, powerful engines. Since sideline noise is measured as the aircraft takes off, a high T/W will increase the sideline noise. However, since there is now more thrust, its climb-out performance is superior and by the time it reaches the fly-over observant, it is at a higher altitude resulting in less flyover noise. Wing area has a similar effect. Increasing wing area improves the climb gradient and reduces flyover noise. The JMP® software allows the user to create a design space where multiple responses can be plotted against two design variables. Constraint values can be added to each response such as a maximum decibel limit for noise or a maximum TOGW allowed. Each response is color-coded and shaded to determine the infeasible region. Any "white" space inside the plot indicates a feasible design region. From this, one can determine with set constraints, what values will generate a feasible design.

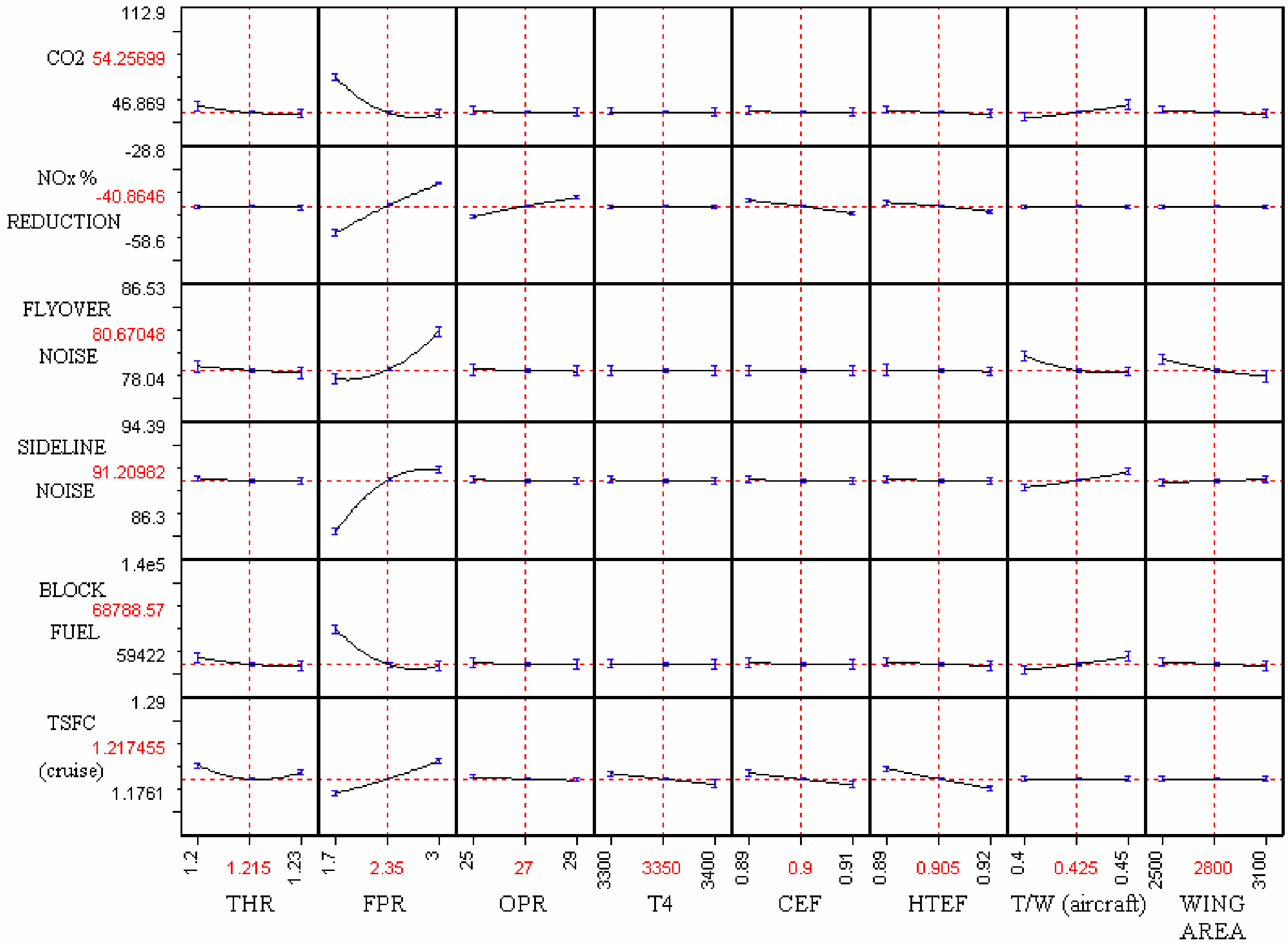

Figure 10: SBJ Propulsion System Dynamic Trade-off Environment.

Figure 11 demonstrates this with sideline and flyover noise, TOGW and approach velocity. The most constraining responses are sideline noise and TOGW. The region in the middle towards the right is an area where all constraints are met.

The trends in both emission metrics are also consistent with what one would expect. Variations in FPR affect CO_2 and NO_x in opposing directions as observed in Figure 12 and Figure 13. NO_x levels are mainly a function of the pressure and temperature entering the combustor. A high overall pressure and temperature indicates high NO_x values. In this study, increasing FPR results in a smaller engine with higher exhaust velocity. More overall compression is needed to attain this thrust, resulting in high NO_x production. Small improvements in compressor and turbine efficiency also aid in reducing NO_x.

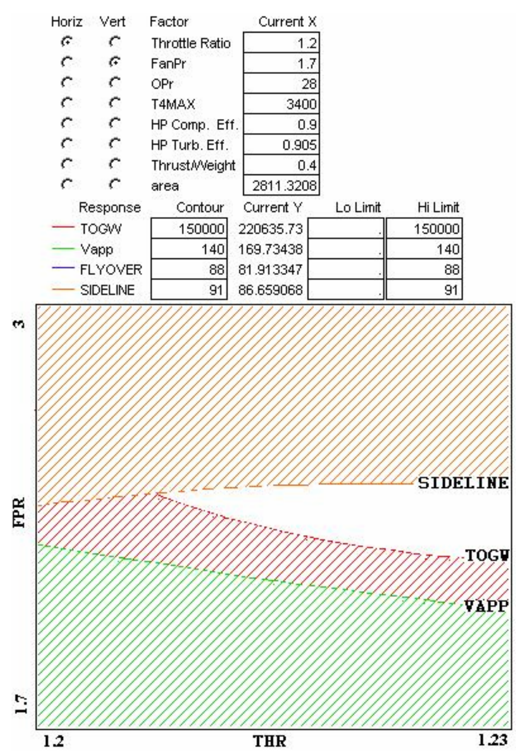

Figure 11: Dynamic "What-if" Trade-off environment.

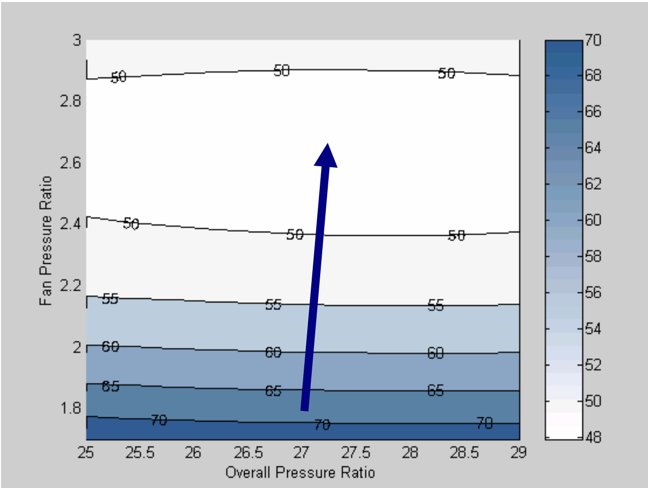

Figure 12: CO_2 (lbs/NM) Variation with FPR and OPR.

Component efficiencies are likewise beneficial in reducing TSFC. Although FPR is significant, the efficiency of the turbine in particular plays a strong role in reducing fuel consumption. Increasing the mass flow into the engine by decreasing the fan pressure ratio will reduce the amount of fuel needed to produce thrust, since the majority of the thrust is provided by the bypass flow. Reducing FPR will generate a low SFC due to improved propulsive efficiency. The prediction profiles also indicate that TSFC decreases while block-fuel increases. The reason is that the FPR is decreasing which results in a larger fan and heavier engine. This causes the TOGW to increase and in turn, more fuel is needed for the mission. Therefore, TSFC should not be regarded as the sole response when analyzing fuel consumption. The quantity of fuel needed for the mission can be opposite to the trend of TSFC.

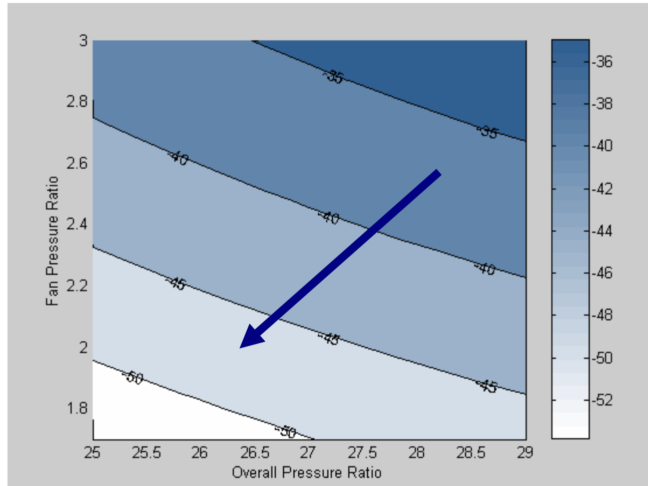

Figure 13: NO_x (% Reduction from 2004 ICAO) Variation with FPR and OPR.

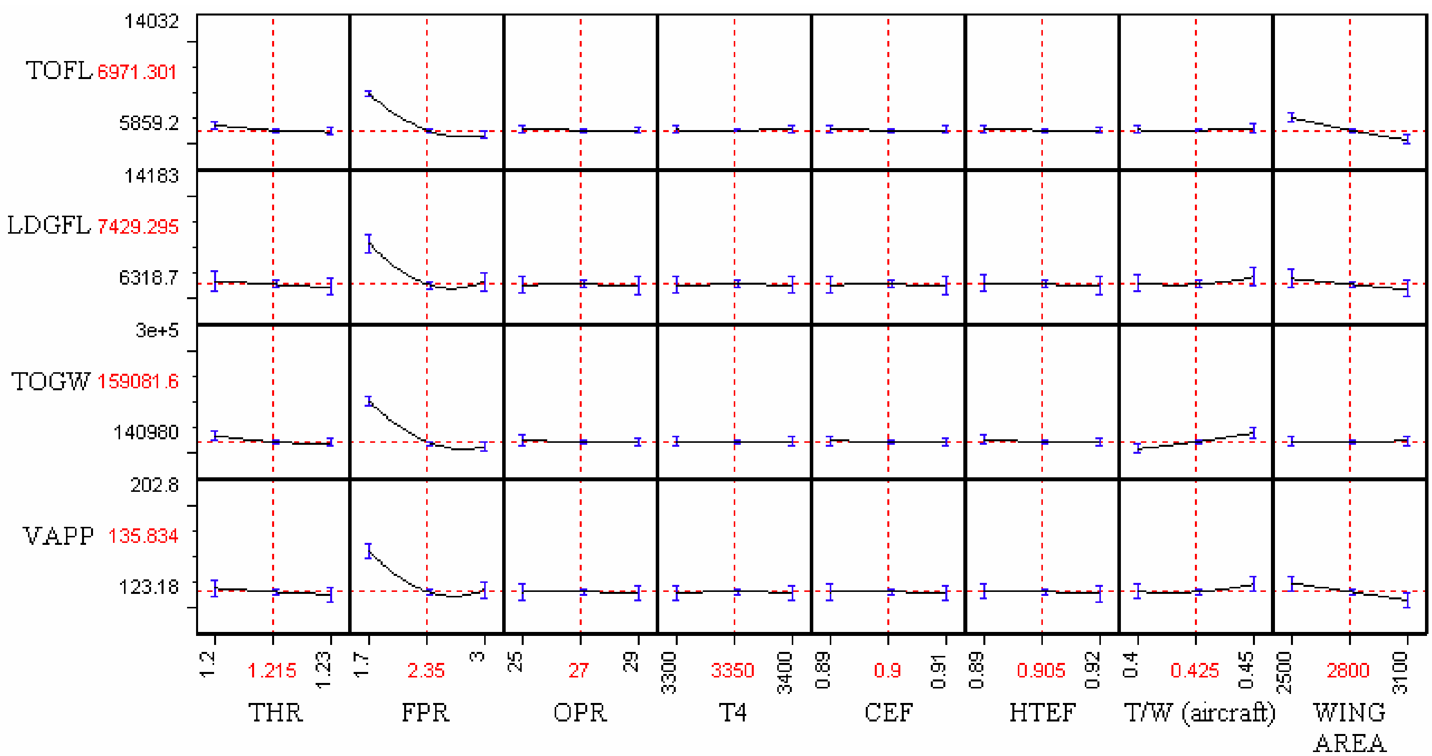

Figure 14: SBJ Propulsion System Dynamic Trade-off Environment for System-Level Metrics

In Figure 14, reducing FPR increases the TOGW and subsequently both field lengths are increased. Since the operation of the SBJ will take place in regional or private airports, it must be capable of taking off and landing within an average 6500 ft runway. In addition, weight is a major participant in the creation of a sonic boom. Trades of design are commonplace in the aerospace industry. Manufacturers from all disciplines must convene in the preliminary design phase and prioritize the metrics whose constraints must be met. In accordance with FAA and ICAO regulations, an optimization study is performed in order to generate an optimized engine and airframe model that satisfies these major constraints. The optimization is carried out using the desirability function in JMP® by deciding to maximize or minimize each response. The software determines the optimum setting for the eight variables which are then fed back into the simulation process in Figure 3 and response results are generated. These are presented below in Table 4.

Optimized Engine and Aircraft Results

	Optimized	*Baseline*	*Constraint*
Total Engine Pod Weight (lbs)	7120	9479	7830
Bypass Ratio	0.67	0.98	-
CO_2 (lbs/NM)	48.1	54.54	50
NO_x (% reduction from 2004)	40	41	-
Flyover Noise (dBA)	82	80	88
Sideline Noise (dBA)	89	91	90
TSFC (cruise)	1.24	1.1984	1.15
TOGW (lbs)	142287	159730	150000
TOFL (ft)	6562	7000	6500
LDGFL (ft)	6688	7321	6500
VAPP (knots)	128	135	140
Aircraft Empty Weight (lbs)	70861	79092	-

Table 4: Optimized Aircraft Responses.

The optimum setting for the eight variables is presented in Table 5 below.

Design Variable	Optimum
Throttle Ratio (THR)	1.215
Fan Pressure Ratio (FPR)	2.35
Overall Pressure Ratio (OPR)	27
Turbine Inlet Temperature (T4) deg. F	3350
High Pressure Compressor Efficiency (CEF)	0.9
High Pressure Turbine Efficiency (HTEF)	0.905
Thrust to Weight of the Aircraft	0.425
Wing Area (ft^2)	2800

Table 5: Optimum Setting for Design Variables.

The majority of the constraints are met including noise and emission values that are most stringent in this design study. These improvements are possible at the expense of TSFC. However, the real goal is to minimize fuel burn, and, as discussed previously, this has been done by meeting the CO_2 goal.

CONCLUSIONS

The primary focus of this study was to determine the technical feasibility of an SBJ engine concept by emphasizing noise, emissions and fuel consumption restrictions. The results of the optimized engine proved to satisfy all major constraints and important mission responses were also successfully met. The optimum engine ended up with 25% less weight. The TOGW also fell by 11%. Another significant result was the reduction in aircraft empty weight by 10%. This translates to enormous payload savings and overall operating costs are decreased. Both field lengths did not meet the constraints imposed but this penalty came as a result of emphasizing noise and emission constraints.

The methodology applied in this study enables designers to introduce more knowledge to early phases of design. The methodology maps propulsion characteristics to overall system metrics such that the entire design space can efficiently be examined. Through this method, the designer essentially has an analytical means to examine every conceivable alternative within the design space. This investigation allows for two insights. First, the impacts of selecting design variables at the micro level can be propagated up to the system level, allowing the designer to synthesize total effects quickly. Second, whether or not the design space being considered is capable of yielding a feasible solution can easily be seen. If a feasible solution exists, the methodology allows for the optimal setting of design variables to be selected. The creation of a meta-model, through RSM greatly enhances the designer's knowledge of the design space. The prediction profilers give the designer a simple, visual representation of the complex system and subsystem level impacts of the changing of design parameters. They allow the decision-maker to play "what-if" games and make tradeoffs in design early, knowing the system level consequences of those tradeoffs. Also, the designer is given an understanding of the magnitude of impacts that different design parameters can have on responses.

FUTURE STUDY PLANS

Further investigations are currently being conducted in this design. As described earlier, an all-encompassing economic analysis has been integrated into the physics-based code sequence by using ALCCA (Aircraft Life Cycle Cost Analysis) [Ref. 1]. Operating costs, acquisition cost and other important metrics for economic viability are incorporated into the design space exploration. In addition, a sonic boom analysis is currently being integrated into this propulsion study.

There are many considerations that should be accounted for in this design study. In supersonic transport design, noise is a major consideration. Designing for supersonic cruise results in low-diameter, high-pressure ratio, low bypass ratio engines which results in much higher jet noise than a high bypass ratio engine. Consequently, this may encourage designers to incorporate a variable design cycle by having higher bypass ratios and lower noise on takeoff and lower bypass at cruise for superior cruise performance. In addition, throttling back on takeoff, when runway length is negligible tends to extend engine life and lower maintenance costs. Further studies include technological infusion processes as detailed [Ref. 2]. This will yield more promising results for noise, emissions and fuel consumption levels.

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